Passive Correction of the Persistent Current Effect in Nb_3Sn Accelerator Magnets

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***Abstract*—Superconducting accelerator magnets must provide a uniform field within the operating range. However, it significantly deteriorates at low fields due to persistent currents induced in superconducting filaments. This effect is especially large for Nb_3Sn superconductor, being implemented in the next generation of accelerator magnets. Simple and inexpensive method of passive correction the persistent current effect was developed and experimentally verified. This paper describes simulations of the persistent current effect, different designs of passive correctors and reports the test results.**

***Index Terms*—Hysteresis, magnetic fields, magnetic materials, superconducting magnets.**

I. INTRODUCTION

SUPERCONDUCTING accelerator magnets must meet certain field quality requirements. In most cases, the low order harmonics at a reference radius must be less than 10^{-4} part of the main field component. However, the field quality significantly deteriorates at low fields due to magnetization of superconducting filaments, caused by persistent currents.

Magnetization of superconducting filament is proportional to the critical current density at given field and effective filament diameter. Modern Nb_3Sn strands, used for accelerator magnets have large critical current density and effective filament diameter that produces magnetization an order of magnitude higher than the last generation of NbTi strands.

Apart from type I superconductors, which are purely diamagnetic, hard superconductors of type II exhibit non-linear magnetization due to field penetration inside the filaments. It results in non-linearity of magnetic field and generation of allowed by coil symmetry multipoles, which are an order of magnitude higher than those acceptable without correction.

Possibility of passive correction the persistent current effect has been studied in the course of development NbTi accelerator magnets. There were considered introduction of passive superconductor [1] or nickel tapes [2] inside the coil aperture, nickel powder inside the strands [3] and permanent magnets [4] for the reduction of the persistent current effect. However, due to their complexity and low efficiency none of proposed techniques found practical implementation in existing accelerators, relied upon the active correction system.

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A simple and effective method of passive correction, based on thin iron strips has been also proposed [5]. Implications of this method including other corrector configurations, results of simulations and tests will be discussed.

II. SIMULATION OF THE PERSISTENT CURRENT EFFECT

Magnetic field in a magnet bore can be described in terms of normalized multipole coefficients according to the expression:

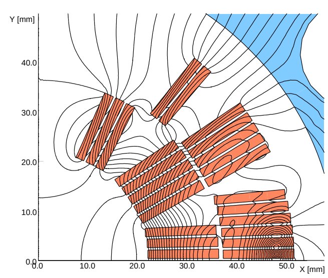
$$B_y(x,y) + iB_x(x,y) = 10^{-4} \times B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1},$$

where $B_x(x,y)$ and $B_y(x,y)$ – horizontal and vertical field components; B_1 – main (dipole) field component; R_{ref} - reference radius; b_n and a_n – normal and skew harmonic coefficients. The reference radius used in this paper is 1 cm.

Simulation of the persistent current effect has been performed using finite-element code OPERA 2D. The method originally described and experimentally verified in [6], retains high precision of vector-potential formulation and allows taking into account measured hysteresis curve for any material.

The coil magnetization was characterized by magnetic properties of IGC Nb_3Sn strand, 1 mm in diameter with a critical current density of 1600 A/mm^2 and Cu/non-Cu ratio of 0.85, measured at Fermilab short sample test facility [7]. The magnetization curve was appropriately adjusted in order to take into account packing factor of strands in the cable and transformed into B(H) curve, suitable for OPERA 2D.

Simulation of the persistent current effect has been performed for the shell type dipole and quadrupole magnets, developed at Fermilab for VLHC. Fig. 1 shows the magnet configurations with flux lines, produced by the persistent currents only (fields from transport current and iron magnetization were subtracted) and Fig. 2-3 present the low order harmonics as function of the field. Persistent current effect in different block type magnets was discussed in [5].



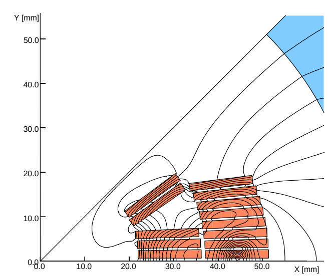


Fig. 1. Magnetization flux in dipole (left) and quadrupole (right) magnets. Flux increment between adjacent lines is kept constant and equal to 5x10^{-5} Wb/m in all similar plots of this paper.

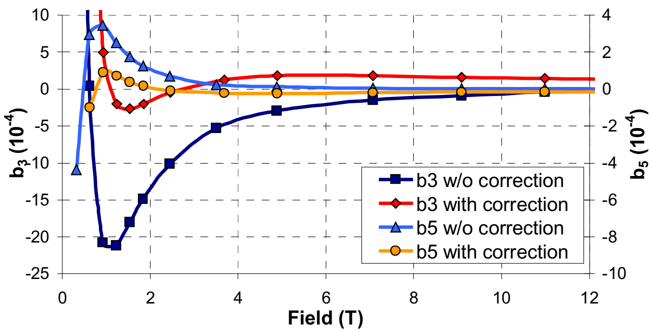


Fig. 2. Low order harmonics in dipole magnet before and after correction.

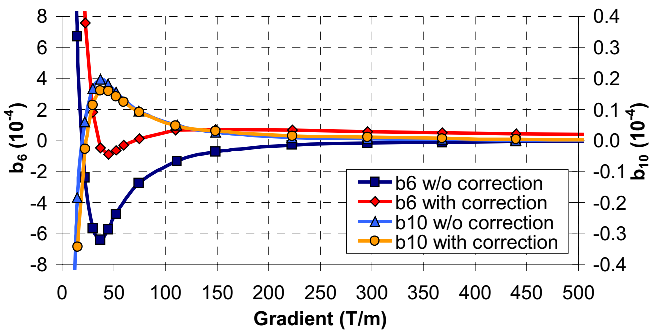


Fig. 3. Low order harmonics in quadrupole magnet before and after correction.

III. Methods of Passive Correction

A. Strips in the aperture

Correction of the persistent current effect in dipole magnets using iron strips in the aperture was described in [5]. It was demonstrated that thin iron strips placed at certain azimuthal positions within the aperture provide effective correction of the persistent current effect.

The same correction technique is applicable for quadrupole magnets. In order to determine the optimum position, a strip with the angular width of 3 degrees and thickness 0.1 mm was aligned on the circular surface with the radius 19.75 mm inside the aperture of quadrupole magnet. The azimuthal strip position was varied within 0-45 degrees with 3 degrees increment. Fig. 4. shows contribution of the strip to low order harmonics at the gradient of 44 T/m (3 kA current), calculated using OPERA 2D. Similarly to the dipole magnet, there is a region where b_6 is positive and b_{10} is negative, making it possible to use one strip for correction of both harmonics.

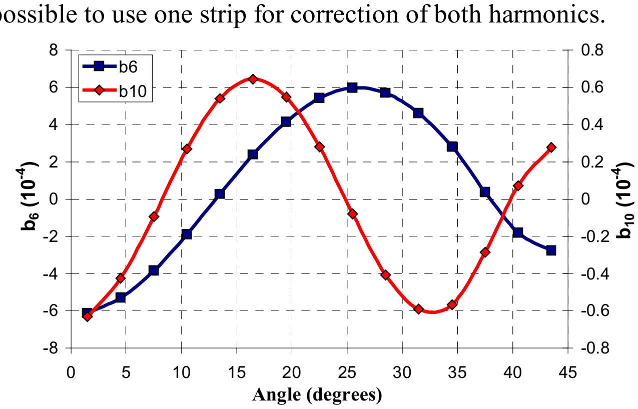


Fig. 4. Harmonics in a quadrupole magnet as a function of the strip position.

B. Strips on the wedges

The correcting strips can also be installed on the wedges, separating coil blocks. In this case, however, number of the design parameters is reduced to one, which is the strip thickness. Therefore, in order to eliminate several low-order harmonics and not affect others, one may need to use larger number of the correcting strips than in case with strips installed inside the coil aperture.

Passive corrector on the coil wedges was studied using OPERA 2D for the dipole and quadrupole magnets. In order to find optimum configurations, an iron strip with 0.1 mm thickness and width equal to the cable width was consistently placed on every coil block surface of the inner layer. Fig.5-6 show contribution of the strip to low order harmonics at 1.2 T field in the dipole and 44 T/m gradient in the quadrupole magnets. Strips numbering starts from the midplane.

Three strips (number 3,4,6) with thickness 0.15 mm, 0.27 mm and 0.15 mm are required per quadrant of dipole coil for the correction of b_3-b_5 harmonics. One strip (number 3) with 0.09 mm thickness is required per quadrant of quadrupole coil for the correction of b_6 component. Due to a relatively small value, correction of b_{10} component was not considered. If needed it may be accomplished by adding ~0.05 mm strip (number 4) to the pole surface.

Fig. 7 shows optimum configurations of the passive corrector inside the coil with magnetic flux lines. One can see that the passive corrector forces the magnetization flux to coincide with the main field component and generate minimum distortions in other harmonics. Low order harmonics before and after correction are presented in Fig. 2-3.

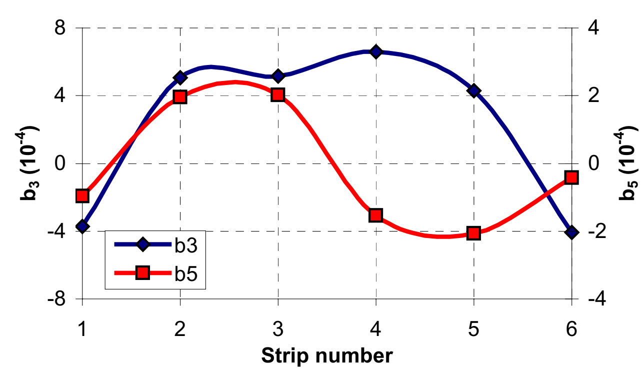


Fig. 5. Harmonics in the dipole magnet as function of the strip number.

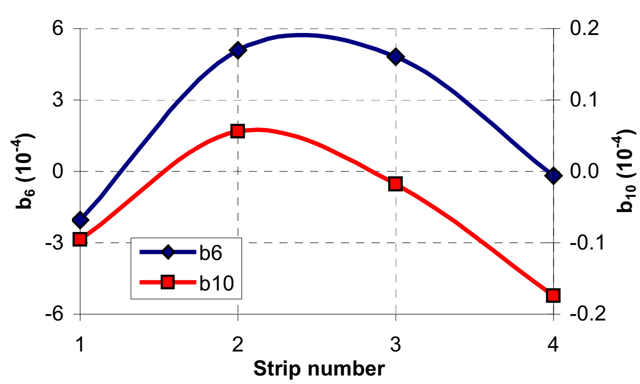


Fig. 6. Harmonics in the quadrupole magnet as function of the strip number.

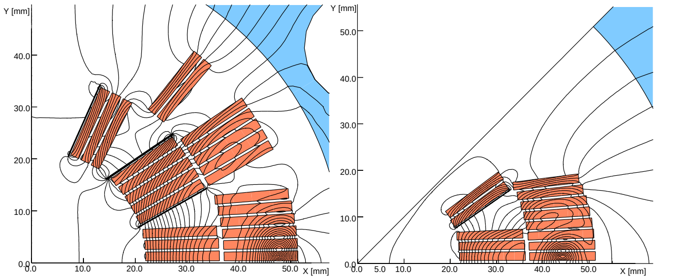


Fig. 7. Magnetization flux in dipole (left) and quadrupole (right) magnets after the passive correction.

The passive correction with strips on the coil wedges provides results similar to the strips inside the aperture. Moreover, in this case the precise strip alignment is automatically provided during the coil winding. It eliminates additional alignment procedures that is essential for manufacturing of long magnets.

Ones placed inside the Nb_3Sn coil, the iron strips can not be removed or somehow altered that requires a precise simulation of the persistent current effect and its correction. Here one can take an advantage from experiments with the iron strips inside the aperture during short model R&D and establish the necessary parameters based on feedback from magnetic measurements. Ones it is done – the passive corrector can be introduced permanently into the coil design.

C. *Strips inside the cable*

A method of passive compensation using iron core inside the cable described in [5] gives opportunity to combine reduction of the coil magnetization effect and interstrand coupling currents, choosing the core material with high electrical resistance, e.g. permalloy. Since magnetizations of superconductor and iron are not exactly symmetrical functions with respect to the applied field, full compensation can be achieved only at some particular field.

Assuming the compensation field of 2.5 T (to have a correcting effect as in the case with strips on the coil wedges), one finds magnetizations M_{sc} = - 0.117 T and M_{fe} = 2.13 T. For an average strands packing factor λ_{sc} = 0.88, the iron packing factor should be λ_{fe} = 0.048. If the iron core takes 2/3 of the cable width – the core thickness should take 7.2 % of the cable thickness or 0.13 mm for 1.8 mm thick cable.

It is 5 times higher than thickness of stainless steel core being routinely used for the reduction of interstrand coupling currents. Such a core reduces the cable flexibility that may create difficulties during the coil winding. Thus, it is possible to achieve only partial compensation of Nb_3Sn magnetization using an iron core of a reasonable thickness.

Nevertheless, the compensating iron core can be successfully (and most naturally) implemented in NbTi magnets. According to [8], at the compensation field of 1 T the NbTi strand magnetization is M_{sc} = - 0.011 T. For the same strands packing factor, iron magnetization and the core width as for Nb_3Sn cable, the strip thickness should be 0.6-0.9 % of the cable thickness or 10-15 μm for 1.8 mm thick cable, which is safe for the coil winding.

IV. Combination of Passive Correction with Coil Optimization

The passive correction of the coil magnetization effect is effective at low fields. However, due to the reason mentioned in previous paragraph, it makes a positive overcompensation at high fields that may need a correction itself. To understand efficiency of the passive correction within the operating field range, it is convenient to represent harmonics in absolute units, where the maximum active corrector contribution is a straight line, parallel to the horizontal axis.

Fig. 7. illustrates the sextupole curves with and without the passive correction. The active corrector should have the maximum strength of $B_3 = \pm 1$ mT/cm^2 in order to eliminate the sextupole component, remaining after the passive correction within at 11 T field. Apart from that, the active corrector has to reverse the current, which is not a well-suited regime for a superconducting magnet.

Nevertheless, just the passive correction itself reduces the active corrector strength by a factor of 2.8 with respect to the non-corrected case. Furthermore, as follows from Fig. 7., the positive part of corrected sextupole curve can be well approximated by a straight line. Since geometrical harmonics (generated by the coil geometry) in absolute units are the straight lines proportional to the field - a cancellation of the linear sextupole part at high fields can be accomplished by introduction an appropriate geometrical harmonic.

Fig. 7. shows the result of introduction the geometrical sextupole (b_3 = -0.86·10^{-4}), which virtually eliminates the magnetization sextupole at fields above 6 T. Then the required active corrector strength is reduced to B_3 = 0.6 mT/cm^2. In this case the active corrector does not reverse its polarity and can be switched off after the field reaches 6 T.

The geometrical correction was also considered for the case without the passive correction. It is necessary to introduce the positive geometrical harmonic (b_3 = 0.66·10^{-4}) to cancel the non-corrected sextupole at 11 T field. However, the minimum on the sextupole curve at 1.5 T field virtually does not change due to a small effect of the geometrical component at low field. It proves that just the coil optimization itself is ineffective for the reduction of the persistent current effect.

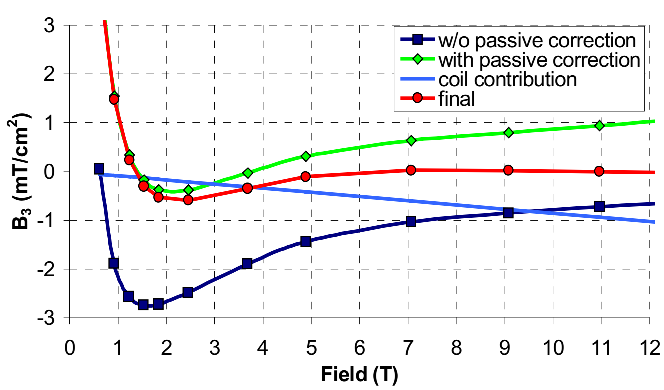


Fig. 7. Elimination of positive overcompensation at high fields.

V. Fabrication and Test of Passive Correctors

Two persistent current correctors with the proposed strips in the aperture geometry were produced in order to test with Nb_3Sn short dipole models. For a simplicity of construction, the corrector was build with one iron strip per coil quadrant, optimized for a positive effect on both sextupole and decapole components. The strip width was 15.85 mm and the thickness was 0.1 mm in the single-strength corrector and 0.2 mm in the double-strength one. The strips were installed between several layers of epoxy-impregnated fiberglass tape at 21.4 mm radius and 55.2 degrees azimuth from the coil midplane to the strip center. Afterwards, the corrector was cured at ~120 °C that formed a rigid fiberglass pipe with the iron strips embedded inside.

The persistent current effect was measured and calculated for the Fermilab Nb_3Sn short dipole models HFDA02, HFDA03. During simulations, magnetization curve measured for the relevant Nb_3Sn strands [8] was used, assuming an additional 10 % of cabling degradation. The persistent current correctors were introduced in the magnet bores between thermal cycles. Measurements of the field harmonics were performed in the magnet center in cases with and without the passive correction at otherwise identical conditions [10].

The measured and calculated values of sextupole and decapole components before and after correction with the single and double strength correctors are shown in Fig. 9-10. It can be seen that the persistent current effect was reduced gradually in two steps with the single and double strength correctors. In the case with double strength corrector, the sextupole curve is virtually flat for the fields above 2 T. Table I summarises the harmonic variations between 1.5 T and 4 T field, calculated and measured with and without correction.

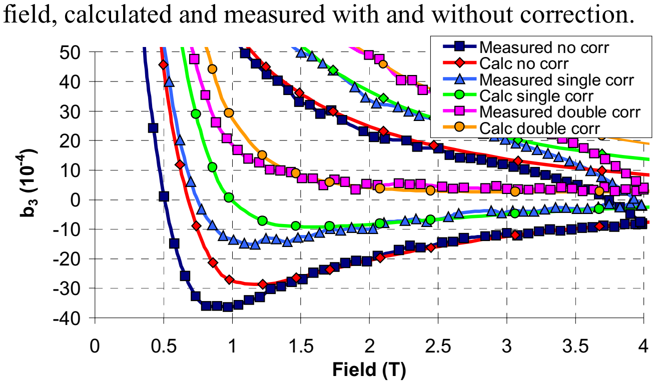


Fig. 9. Normal sextupole before and after correction.

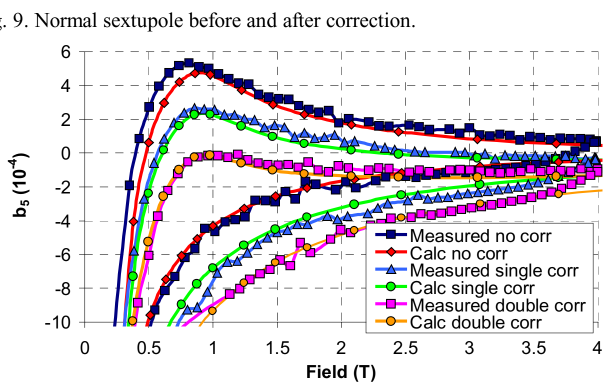


Fig. 10. Normal decapole before and after correction.

Table I
Harmonic Variations in 1.5-4 T Range

Correction type	Δb_3, 10^{-4}		Δb_5, 10^{-4}	
	Calc.	Meas.	Calc.	Meas.
No correction	18.9	19.4	2.4	2.4
Single strength	7.3	11.0	1.4	1.7
Double strength	4.4	3.7	0.4	0.3

Reasonable correlation of between calculations and measurements validates possibility of precise prediction and correction of the coil magnetization effect in Nb_3Sn accelerator magnets using thin iron strips.

VI. Conclusion

Persistent current effect was simulated in the dipole and quadrupole magnets based on Nb_3Sn superconductor. The field quality distortions were unacceptably large and needed correction. Simple and effective methods of passive correction the persistent current effect based on thin iron strips were developed. An approach to eliminate passive overcompensation at high fields and enhance the effect of passive correctors based on a small adjustment of the coil geometry was proposed.

Two passive correctors of the persistent current effect were manufactured and tested with Nb_3Sn models. High corrector efficiency for the reduction of the persistent current effect was experimentally confirmed. Good correlation between calculations and measurements justifies a possibility of the precise simulation the persistent current effect and passive correction based on the iron strips.

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